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Functional Requirement Specification
PIP-II MPS FRS
ED0004250, Rev. -

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Revision control is managed via Fermilab Teamcenter Workflows.

Rev.	Date	Description	Originated By	Section No.	Approved By
-	JAN. 5/ 2016	Initial release		*ALL*	*As signed*
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1. Introduction:

PIP-II is a high intensity proton linac conceived to support a world-leading physics program at Fermilab [1]. Initially PIP-II will provide high intensity beams for Fermilab neutrino program with future extension to other applications requiring CW linac operation (e.g. muon experiments). PIP-II is a 2 mA CW, 800 MeV H- linac that should be capable of working initially in a pulse (0.55 ms, 20 Hz) mode for injection into the Booster.

The PIP-II Machine Protection System (MPS) is a part of a broader Fermilab complex MPS responsible for protection of equipment in PIP-II and downstream machines from damage induced by the PIP-II linac beam. The damage could be caused by component failures or operator errors and could range from melting the vacuum chamber components to slow degradation of SRF cavities from excessive beam loss inside cryomodules. This document specifies the responsibilities of the MPS, the level of beam losses triggering the beam interruption and the interruption time scale. It also specifies the main triggering processes and the beam interruption devices.

2. MPS responsibilities:

The PIP-II MPS comprises a logic system that takes in signals from various systems and drives permits to beam enabling devices.

The PIP-II MPS has the following responsibilities and features:

1. Safely switch off the beam in the case of failures or operator request.
2. Determine the operational readiness of the machine.
3. Manage alarm limits and provide alarm information to control system.
4. Provide a comprehensive overview of the machine status.
5. Provide time-stamped, post mortem analysis after a fault.

3. Device hierarchy:

The devices interacting with MPS are divided into two categories, primary and secondary, which differ by their criticality for the machine protection and, correspondingly, by the level of the applied scrutiny. Both categories include sensing and beam-shutting devices.

The set of primary devices should guarantee that, when they function properly, no dramatic damage can be caused by the beam even if protection through secondary devices fails. The set of primary devices should be listed in the Technical Requirement Specifications (TRS) of PIP-II MPS, and, after commissioning of the MPS, any modifications to their functioning can be made only with approval of the MPS coordinator with subsequent testing of the affected parts. The description of the primary system in TRS should include a procedure for testing of its operational readiness.

The primary devices include

1. A signal from the downstream machines indicating their readiness for the PIP-II beam
2. A system comparing the beam current at various locations along the accelerator starting from the downstream MEBT end
3. LEBT chopper, LEBT dipole, Ion Source modulator, Ion Source bias power supply as beam-shutting devices

The primary devices cannot be masked.

The secondary category comprises devices whose malfunctioning cannot create dramatic damage either because the effect can be detected and mitigated by primary devices or because the reason for inclusion of the device into MPS is protection of the device itself (e.g. insertion devices). The secondary devices further decrease the probability of damage and possible irradiation of components. The list of secondary sensing devices includes

1. Status signals from subsystems. A malfunctioning subsystem affecting the beam delivery (e.g. RF amplifier) should drop the beam permit.
2. Vacuum gauges and valves
3. Positions of insertion devices
4. Indicators of beam losses (e.g. radiation monitors, current from scrapers induced by the beam)

Examples of beam-shutting secondary devices are the MEBT chopper, switching magnets and separators that can prevent the beam entering an alarmed area.

General protocols of interaction between the secondary devices and MPS should be described in PIP-II MPS TRS, while details of specific levels and timings may be described separately.

Detection of beam losses in the warm front end is performed by the secondary devices, first of all, by the scraping system. Complicated trajectory, varied from bunch to bunch, and the beam structure changing along the beam line, make impractical to designate a small set of devices to be primarily responsible for the beam loss detection. On the other hand, lower beam power density, lower sensitivity of the warm elements to beam losses and their lower cost decrease the potential for the critical beam – induced damage. Robustness of the warm front end should be achieved by redundancy in secondary devices protecting the warm front end.

4. Specifications for PIP-II MPS primary system:

a. MPS Interaction with the broader Fermilab Accelerator Complex:

The fault signal from the MPS of the downstream machines or experiments using the Linac beam should shut the beam at the entrance of RFQ off within 10 μs after the PIP-II MPS receives the signal.

A separate interface document should describe interaction with the MPS of Fermilab Accelerator Complex, including time requirements and protocols.

b. Issuing the fault signal from beam loss:

The primary beam current comparing system should identify the beam loss as a difference between readings in specified locations and drop the beam permit if it detects a beam loss of

- >500 μA while averaged over 1 μs sliding time window
- > 5 μA averaged over one power line period (1/60 s) for operation in CW regime

c. Deviation from the expected pattern:

The primary system should drop the permit if it detects a large deviation of the measured beam pattern from the expected one. The deviation is deemed large when the average current measured in 30 μs sliding time window exceeds the expected value by more than 20% of the beam current or 20 μA, whichever is larger.

d. Shutting off the beam:

The beam can be shut off in one or two steps.

Step 1: The beam is shut off by the LEBT chopper within 10 μs after a system drops the beam permit. This time is measured as difference between moments of the permit dropped in the location of the failure and disappearance of the beam at the entrance of the RFQ.

Step 2: If the average beam current measured by designated primary system devices doesn't drop below measureable level after 15 μs, the Ion Source modulator, LEBT dipole and the Ion Source bias power supply are turned off.

MPS should be capable of initiating both steps at once in cases considered as potentially severe. The procedure with one-step shut-off option is used for the cases where a quick recovery is expected.

e. Latching:

The MPS should be capable to assign different latching scenarios to different events:

- Restoring the beam automatically after a specified time delay if the beam permit is back
- Requiring an operator command to restart the beam

5. References:

PIP-II documents are referred by their numbers in TeamCenter.

[1] PIP-II Functional Requirements Specification, ED0001222,